ARMY RESEARCH LABORATORY

Impact Effects in Multilayered Plates

by Jonas A. Zukas
and Daniel R. Scheffler

ARL-TR-2223

April 2000

Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-TR-2223 **April 2000**

Impact Effects in Multilayered Plates

Jonas A. Zukas
Computational Mechanics Consultants, Inc.

Daniel R. Scheffler
Weapons and Materials Research Directorate, ARL

Abstract

This report presents results of numerical simulations of impact effects in monoblock and mulitlayered plates using both Lagrangian and Eulerian wave propagation codes. It is found that Lagrangian simulations compare favorably with experimental and analytical results. Eulerian codes, while ideal for large distortion situations such as penetration, have great difficulty in describing multiplate perforation due primarily to problems with the interface treatment in Eulerian codes.

This report was originally presented as a paper at the Special Symposium Honoring the 70th Birthdays of Professors Jack Vinson and Charlie Bert, which was part of the 1999 ASME International Mechanical Engineering Congress and Exposition held in Nashville, TN, on 14–19 November 1999. The paper has been accepted for publication in a special volume of *The Journal on Solid and Structures.*

Acknowledgments

The authors would like to thank Dr. Steven B. Segletes who served as technical reviewer for both the original symposium paper and this technical report version of the original. His thorough review and comments helped improve both the paper and report.

INTENTIONALLY LEFT BLANK.

Table of Contents

INTENTIONALLY LEFT BLANK.

List of Figures

INTENTIONALLY LEFT BLANK.

1. Introduction

Impact and impulsive loading onto layered media (targets consisting of different materials) is a long standing problem. It occurs naturally when dealing with impact effects in geological media where different strata have different material properties. It can occur in the design of protective structures where materials of different density, strength, and cross-sectional area are employed to reduce the intensity of the impact stress. Many examples can be found in the works of Rinehart [1] and Tedesco and Landis [2]. This aspect of the impact problem is well understood and covered in modern textbooks and reference books dealing with transient phenomena.

One aspect of layering involves the impact of projectiles onto targets consisting of multiple layers of plates of the same density. In impact testing, this often occurs when very thick targets need to be constructed, yet the material is not manufactured in the required thickness. One example is the requirement to construct a "semi-infinite" target, one where the rear of the plate does not influence the penetration process. The total thickness can be made up by stacking identical layers of smaller thicknesses to reach the desired target thickness. This target stack is then contained in some fashion (e.g., strapped or welded at the periphery). The situation also arises in laboratory tests when measuring wave arrival times or pressures in situ. The method by which probes are inserted in the target can dramatically change wave propagation behavior. Netherwood [3], conducting in situ pressure measurements of impacted plates, found that multilayer targets are much weaker than solid ones of the same thickness; therefore, the mechanism of penetration was distinctly different for the two types of targets. Nixdorff [4] analytically examined the effect of lamination on the ballistic limit for up to five layers, and found considerable differences as the number of layers increased. Segletes and Zukas [5] and Zukas [6], in numerical studies of layered targets with Lagrangian codes, obtained similar results.

Multilayer targets can be grouped into three classes:

(a) thin targets ($T/D < 1$, where T = target thickness and D = projectile diameter)
(b) intermediate thickness targets ($3 < T/D < 10$)

(c) thick targets (T/D > 10)

Zaid, El-Kalai, and Travis [7], Eleiche, Abdel-Kader, and Almohandes [8], and Gupta and Madhu [9] (as well as the previously cited references) found that for thin targets, the multilayer plate is much weaker than the solid one of the same thickness. Other studies could be cited, but these studies suffice to show that for thin targets, lamination can alter the response mechanism under impact loading and fail to correlate with the behavior of a solid target, especially if the number of layers is large.

For thick targets, correlation between impact effects in a solid target and one made of layers of identical material can be quite good, especially for T/D ratios that are very large. Care must be taken to insure that the target is sufficiently large in the radial direction so that boundary effects do not influence penetration phenomena [10].

The response of intermediate thickness targets can exhibit characteristics of both thin and thick target response, depending on T/D, material properties, striker geometry, and initial conditions.

2. Intermediate Thickness Targets

2.1 Lagrangian Calculations. The problem for intermediate thickness targets can be seen from the following calculations. The ZeuS code [5,11,12], a two-dimensional, Lagrangian explicit finite element code for fast, transient analysis on personal computers, was used to calculate the impact of a 64.5-g S-7 tool steel projectile with length-to-diameter (L/D) ratio of five into a single rolled homogeneous armor (RHA) plate with a thickness of 3.18 cm. The projectile had a diameter of 1.3 cm and a striking velocity of 1,164 m/s. Experimental data were taken from the report by Lambert [13]. The experimentally determined values of residual mass and residual velocity were 22.9 grams and 223 m/s, respectively. ZeuS calculations indicated a residual mass of 25.5 g and a residual velocity of 233 m/s. These results were deemed acceptably close. Material properties for the calculations were taken from split-Hopkinson bar results published by Nicholas [14].

Next, a series of calculations was performed where the solid target was assumed to consist of two, four, and six layers, each with properties identical to those of the solid target. Figure 1 shows penetration of the four-layer target at various times. The variation of projectile normalized residual mass (m_r/m_0) and normalized residual velocity (V_r/V_s, where V_s is the striking velocity) can be seen in Figures 2 and 3. With the four-layer target, the difference between Lambert's data for the solid target and the computed residual masses is 43%, while for the residual velocity it is 143%. The differences continue to increase with additional layering.

Even though the plates in the multilayer target have the same density and material properties as the solid target, the differences noted could be anticipated. The plates in the multilayer target are not restrained; hence, they can slip freely over each other. As they separate, a free surface is created. The inability of a free surface to support rarefaction waves changes the stress wave propagation characteristics of multiplate penetration events at early times. As these stress variations are integrated in time, the difference between the simulations becomes more visible, with the multiplate case demonstrating more bending than the equivalent solid plate case (Fig. 4). This can also be inferred from plate theory, which gives for the bending stiffness of the plate $D = ET^3/12(1-\upsilon^2)$, where E is the elastic modulus, T the plate thickness, and υ Poisson's ratio. Since bending stiffness follows plate thickness to the third power, simply cutting a monoblock plate in half reduces its bending stiffness by a factor of eight.

There is no direct experimental evidence for the behavior of the layered plate. However, we can establish confidence in the validity of the Lagrangian calculations from the following considerations. First, the calculation for the residual mass and velocity of the monolithic plate agree closely with the experimental data of Lambert, cited previously. Second, Eleiche, Abdel-Kader, and Almohandes [8] present experimental data for impacts into steel and fiberglass-reinforced polyester (FRP) plates consisting of one to eight layers. Some target arrays consist of plates in direct contact, while others include air gaps ranging from one to three plate thicknesses. Their experiments were conducted with thinner plates (8 mm) than considered here, yet show the same trends; the normalized residual velocity ranged from 0.62 for a single plate perforation to 0.73 for perforation of a stack of eight plates, with a total thickness equivalent to that of the single plate. Finally,

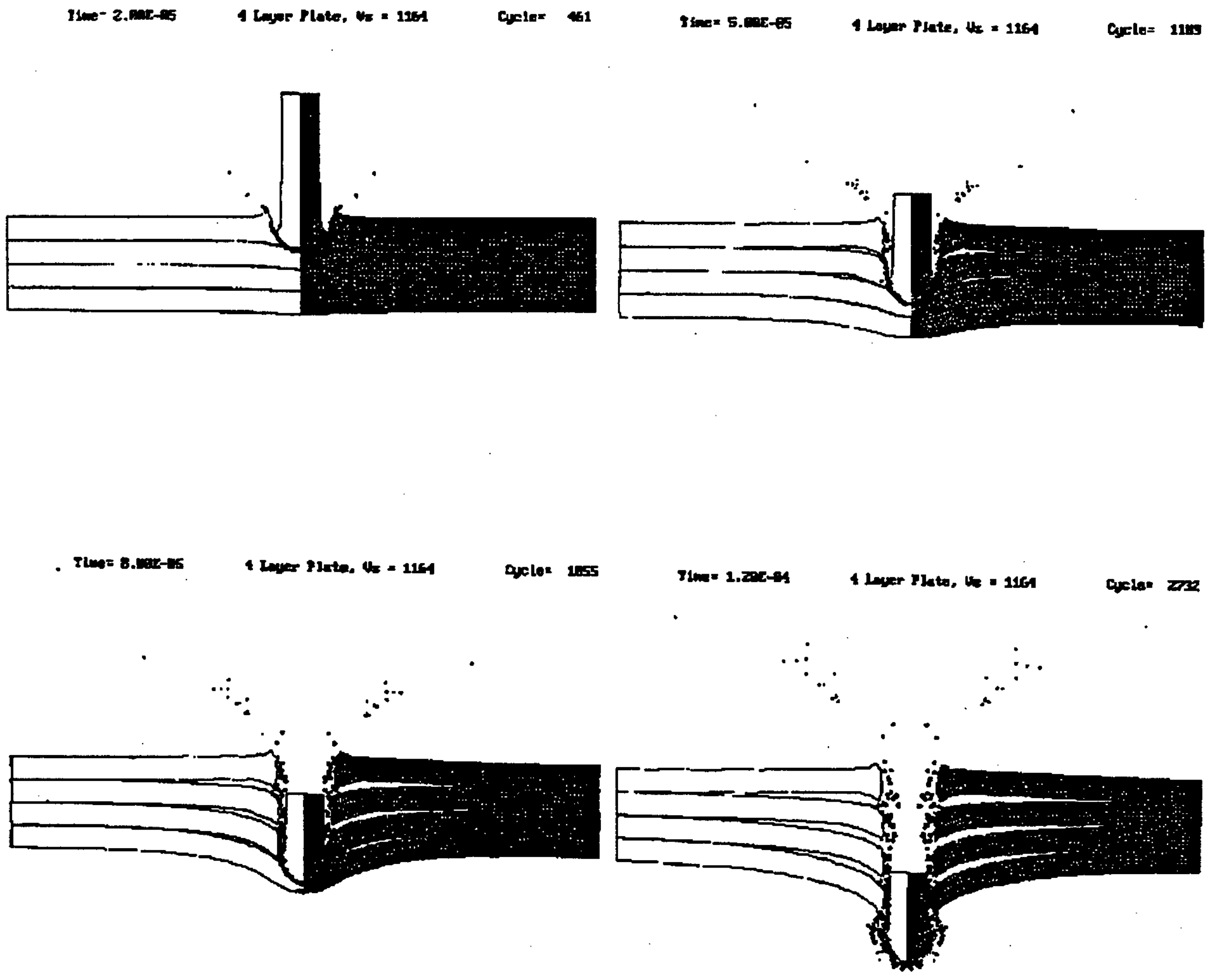

Figure 1. Perforation of a Laminated Plate.

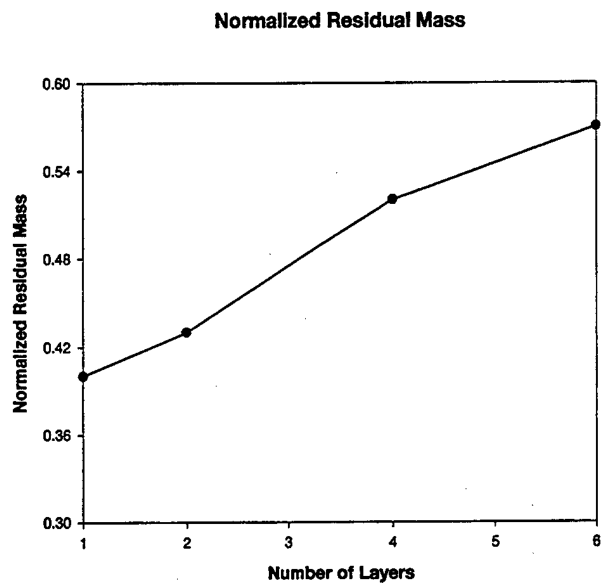

Figure 2. Variation of Projectile Residual Mass With Target Layering.

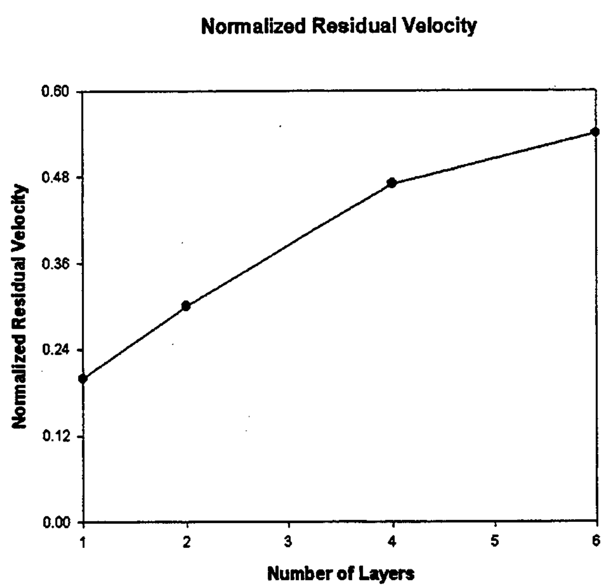

Figure 3. Variation of Projectile Residual Velocity With Target Layering.

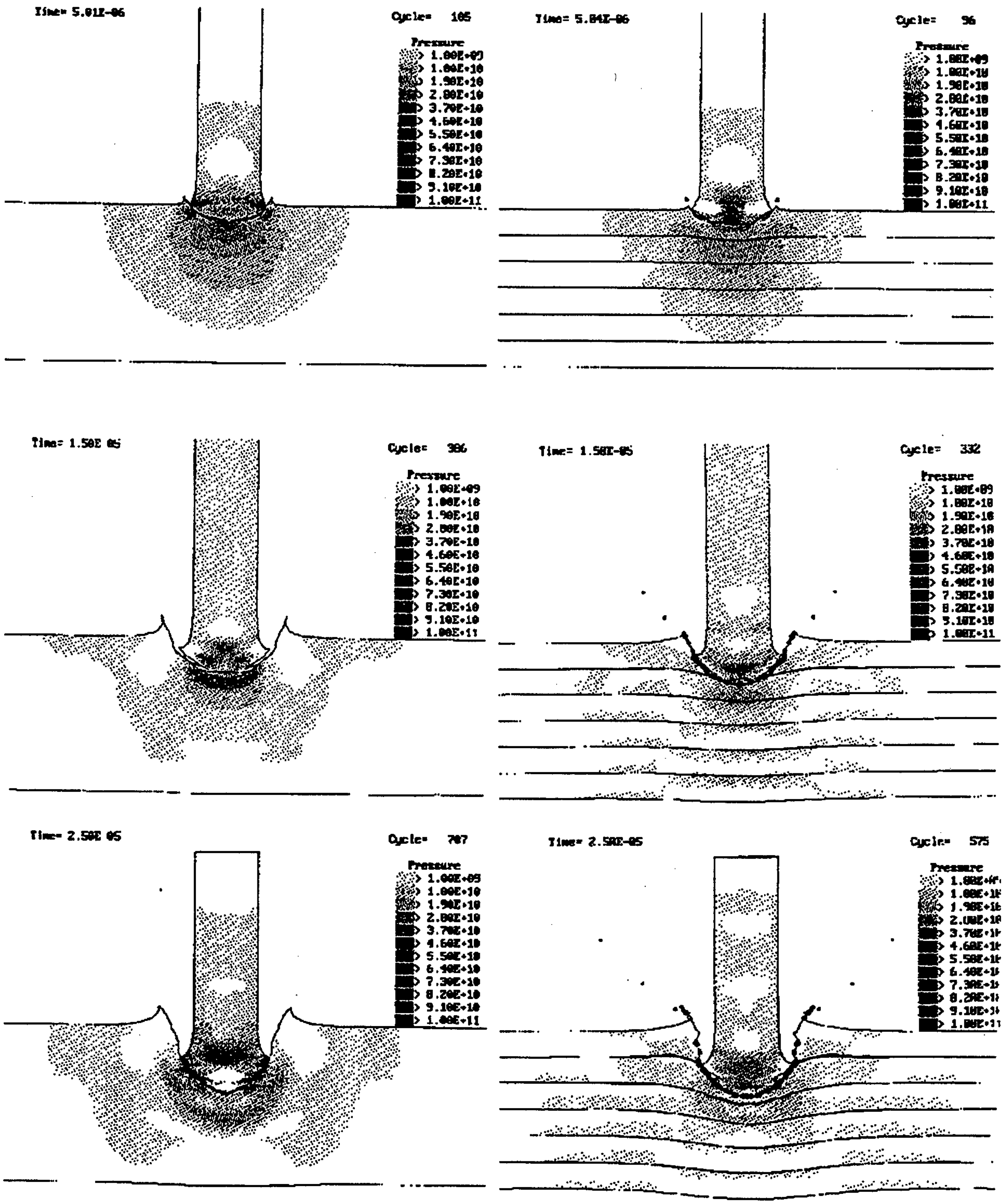

Figure 4. Wave Propagation in Solid and Six Layer Target.

Nixdorff [4], using penetration theories of Awerbuch and Bodner and Lambert and Jonas (both described in Chapter 5 of Zukas et al. [15]), analytically studied the variation in the ballistic limit with the number of plate layers, holding the total plate thickness constant. Nixdorff found that for targets that were subdivided into n layers of equal thickness ". . . the residual velocity has always turned out to be higher, the ballistic limit velocity has always turned out to be lower than for a monolithic target of the same total thickness. This becomes globally more apparent when the number n of subdivisions is raised while keeping the total thickness constant."

2.2 Eulerian Calculations. The January 1998 version of the Eulerian CTH hydrocode [16] was used to model the previously discussed Lagrangian simulations. A series of four simulations was conducted corresponding to a single target plate and two, four, or six plate-layered targets with the same initial conditions as the Lagrangian simulations. All simulations used a mesh consisting of 480 × 800 cells with a one-to-one aspect ratio throughout. The size of the cells provided 20 cells across the radius of the penetrator. To model sliding between plates, a 0.01 cm gap was introduced between each plate. Additionally, mixed cells were not allowed to support tension.

Figure 5 shows the predicted normalized residual mass as a function of the number of target layers. Because CTH only gives the mass for the individual materials as a global quantity including all material in the mesh, the mass of the residual penetrator had to be estimated. To estimate the residual mass a damage criterion was chosen (damage in the sense of the Johnson-Cook failure model [17] in which material with a damage of 1.0 is assumed fully failed and behaves as a fluid) in which all penetrator material with a damage of 0.99 or greater was assumed to no longer contribute to residual mass. Using this criterion, the Eulerian simulations overpredicted the experimentally determined residual mass for the single-plate target. Additionally, the Eulerian simulations show little sensitivity in predicted residual mass as a function of the number of target layers. The computed residual masses were 39.85 g, 40.57 g, 40.31 g, and 40.52 g for the one, two, four, and eight target-plate layers, respectively.

Residual velocity was predicted to be relatively constant by CTH, at 840 m/s for the monolithic plate and 850 m/s for all layered plate configurations. The lack of sensitivity of the

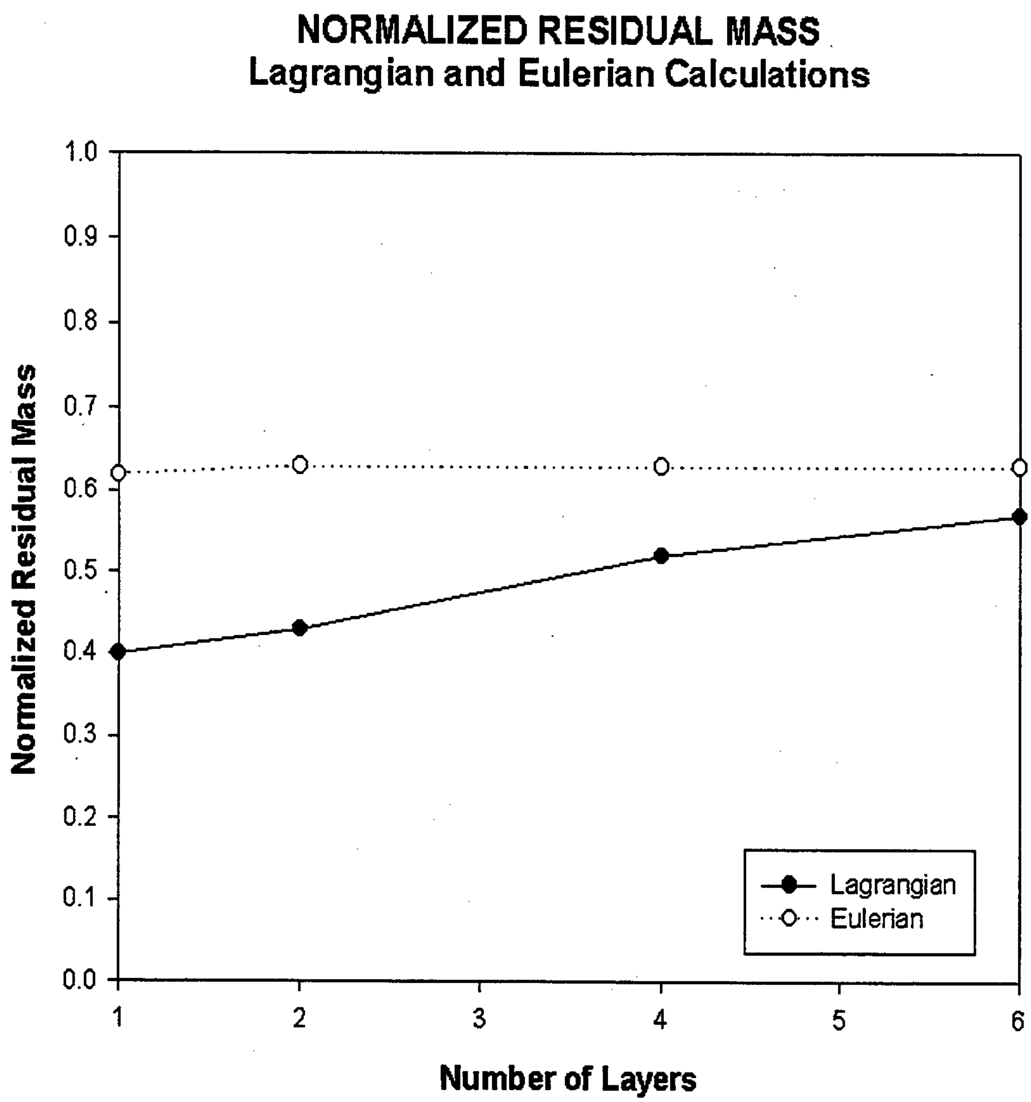

Figure 5. Variation of Projectile Residual Mass With Target Layering Comparing Lagrangian and Eulerian Simulation Results.

results can be explained by the interface treatment used. Eulerian simulations are usually advanced in two distinct phases. In the Lagrangian phase, the mesh is allowed to distort and the simulation is advanced in time. In the advection phase, the distorted mesh is remapped back to the original mesh. The velocities in Eulerian codes are either defined at the cell faces (as in CTH) or at the cell corners (nodes), and all other flow-field variables are cell centered. The implication is that all materials within a mixed cell have the same velocity field, implying a no-slip condition. An attempt to overcome this shortcoming in the CTH code has been made by Walker and Anderson [18]. The authors defined a cell-centered velocity where each material within a mixed cell had its own velocity, which was advected with the material as a state variable. The authors attempted modeling a rigid body perforation with only limited success.

When materials separate, free surfaces are created and stress pulses cannot cross these surfaces. In the Eulerian simulations, the plates were initially separated by 0.1 mm, but this was still less than the width of a single cell; therefore, the free surfaces were in mixed cells. As a result, compressive stress pulses could still pass over the free surfaces even when the individual plates were not in physical contact. For tensile stresses, void is inserted over several computational cycles to relax pressures and allow materials to separate. In the simulations presented here, mixed cells were not allowed to support tension; however, a tensile wave arriving at the interface between target plates will not act as a free surface, as relaxing the stresses by inserting void takes place over several computational cycles.

Today, the simple failure models in hydrocodes are the single biggest limitation of code accuracy. The Lagrangian and Eulerian codes used in this study had different failure models. The effect of these on computational results has not been examined. Failure is modeled only in the grossest sense in both sets of calculations. In the Lagrangian simulations, failure was largely controlled through an ad hoc erosion algorithm in which elements are removed when they reach a user-defined value of equivalent plastic strain (erosion strain). Failure occurs at two levels. At a value of effective plastic strain of 0.40, the elements are no longer able to carry shear or tensile stresses. Only compression is permitted, so the material behaves much as a fluid. At a much higher value, typically between 1.2 - 1.5 in most calculations, the material is assumed to have failed totally.

Failed elements are removed from the calculation, the contact surfaces are redefined for each geometry, and the calculation proceeds. Since mass points associated with failed elements continue to be tracked, this procedure conserved mass and momentum exactly, but total energy only approximately. The Eulerian simulations used the emperical Johnson-Cook damage model with parameters chosen so that material would fail at an equivalent plastic strain of 0.40.

Lagrangian codes provide a straightforward means of defining material interfaces but have problems treating large deformation. On the other hand, Eulerian codes readily treat severe deformation but have certain disadvantages modeling sliding and handling material properties within mixed cells. A potential solution is to use a finer mesh so that several empty cells (void cells) are between the individual plates. Problems, however, would still occur when the initially separated plates come into physical contact.

3. Conclusions

Layering dramatically weakens targets of thin and intermediate thickness. For very thin targets, even the mechanism of penetration may change, while thick targets show small changes in projectile residual properties when compared to their monoblock equivalents.

Lagrangian calculations can do an excellent job of simulating monoblock and multiplate perforation if: (1) care is taken to determine material properties for the constitutive model from wave propagation experiments at appropriate strain rates, and (2) some reasonable estimate of material failure is used. Results of Euler code calculations are very sensitive to the material interface logic used in the code. Despite an appropriate constitutive model and parameters for that model obtained from wave propagation experiments, incorrect results may be obtained in relation to experiments depending on the material transport algorithm chosen.

4. References

1. Rinehart, J. S. "On Fractures Caused by Explosions and Impacts." *Quart Colorado School of Mines*, vol. 55, no. 4, 1960.

2. Tedesco, J. W., and D. W. Landis. "Wave Propagation Through Layered Systems." *Computers & Structures*, vol. 32, nos. 3–4, 1989.

3. Netherwood, P. H. "Rate of Penetration Measurements." ARBRL-MR-02978, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1979.

4. Nixdorff, K. "Some Applications of the Impact Theory of J. Awerbuch and S. R. Bodner." *Trans CSME*, vol. 8, no. 1, pp. 16–20, 1984.

5. Segletes, S. B., and J. A. Zukas. "The Effect of Material Interfaces on Calculations of Plate Penetration." *Recent Advances in Impact Dynamics of Engineering Structures*, edited by D. Hui and N. Jones, AMD-Vol. 105, New York: ASME, 1989.

6. Zukas, J. A. "Effects of Lamination and Spacing on Finite Thickness Plate Perforation." *Structures Under Shock and Impact IV*, edited by N. Jones, C. A. Brebbia, and J. A. Watson, Southampton: Computational Mechanics Publications, pp. 103–115, 1996.

7. Zaid, A. I. O., A. El-Kalai, and F. W. Travis. "An examination of the Perforation of Mild Steel Plate by a Flat-Ended Cylindrical Projectile." *International Journal of Mechanical Sciences*, vol. 15, pp. 129–143, 1973.

8. Eleiche, A. M., M. S. Abdel-Kader, and A. Almohandes. "Penetration Resistance of Laminated Plates from Steel and Fiberglass-Reinforced Polyester." *Structures Under Shock and Impact IV*, edited by N. Jones, C. A. Brebbia, and A. J. Watson, Southampton: Computational Mechanics Publications, pp. 117–126, 1996.

9. Gupta, N. K., and V. Madhu. "An Experimental Study of Normal and Oblique Impact of Hard-Core Projectiles on Single and Layered Plates." *International Journal of Impact Engineering*, vol. 19, nos. 5–6, pp. 395–414, 1997.

10. Littlefield, D. L., C. E. Anderson Jr., Y. Partom, and S. J. Bless. "The Penetration of Steel Targets Finite in Radial Extent." *International Journal of Impact Engineering*, vol. 19, no. 1, pp. 49–62, 1997.

11. Janzon, B., N. Burman, J. Forss, and E. Liden. "EFP Modeling by Numerical Continuum Dynamics on Personal Computers - A Comparison Between PC-DYNA2D, ZeuS, and AUTODYN." *Proceedings of the 13th International Symposium on Ballistics*, Stockholm, Sweden, 1992.

12. Zukas, J. A. "Some Common Problems in the Numerical Modeling of Impact Phenomena." *Computing Systems in Engineering*, vol. 4, no. 1, pp. 43–58, 1993.

13. Lambert, J. P., "The Terminal Ballistics of Certain 65 Gram Long Rod Penetrators Impacting Steel Armor Plate." ARBRL-TR-02027, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 1978.

14. Nicholas, T. "Material Behavior at High Strain Rates." AFWAL-TR-80-4053, USAF Wright Aeronautical Laboratories, Wright-Patterson Airforce Base, OH, 1980.

15. Zukas, J.A., T. Nicholas, L. B. Greszczuk, H. F. Swift, and D. R. Curran. *Impact Dynamics*, New York: Wiley, 1982; Republished Malabar, FL: Krieger, 1992.

16. McGlaun, J. M., S. L. Thompson, and M. G. Elrick. "CTH: A Three-Dimensional Shock Wave Physics Code." *International Journal of Impact Engineering*, vol. 10, nos. 1–4, pp. 251–360, 1990.

17. Johnson, G. R., and W. H. Cook. "Fracture Characteristics of Three Metals Subjected to Various Strains, Strain Rates, Temperatures, and Pressures." *Journal of Engineering Fracture Mechanics*, vol. 21, no. 1, pp. 31–48, 1985.

18. Walker, J. D., and C. E. Anderson Jr. "Multi-Material Velocities for Mixed Cells." *High Pressure Science and Technology - 1993*, edited by S. C. Schmidt, J. W. Shaner, G. A. Samara, and M. Ross, Woodbury, NY: American Institute of Physics, pp. 1773–1776, 1993.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDQ D SCHMIDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDDR&E(R) R J TREW THE PENTAGON WASHINGTON DC 20301-7100
1	DPTY CG FOR RDA US ARMY MATERIEL CMD AMCRDA 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797
1	DARPA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	NAVAL SURFACE WARFARE CTR CODE B07 J PENNELLA 17320 DAHLGREN RD BLDG 1470 RM 1101 DAHLGREN VA 22448-5100
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MADN MATH THAYER HALL WEST POINT NY 10996-1786

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL DD 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AS (RECORDS MGMT) 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
	<u>ABERDEEN PROVING GROUND</u>
4	DIR USARL AMSRL CI LP (BLDG 305)

NO. OF COPIES	ORGANIZATION
1	US ARMY DUSA OPS RSCH D WILLARD 102 ARMY PENTAGON WASHINGTON DC 20310-0102
5	DEFENSE NUCLEAR AGENCY MAJ J LYON CDR K W HUNTER T FREDERICKSON R J LAWRENCE SPSP K KIBONG 6801 TELEGRAPH RD ALEXANDRIA VA 22310-3398
3	COMMANDER US ARMY ARDEC AMSTA AR FSA E W P DUNN J PEARSON E BAKER PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH V M D NICOLICH PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC E ANDRICOPOULOS PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER USA STRATEGIC DEFNS CMD CSSD H LL T CROWLES HUNTSVILLE AL 35807-3801
3	COMMANDER US ARMY AVIATION & MISSLE CMD AMSAM RD PS WF S HILL D LOVELACE M SCHEXNAYDER REDSTONE ARSENAL AL 35898-5247

NO. OF COPIES	ORGANIZATION
1	MIS DEFNS & SPACE TECHNOLOGY CSSD SD T K H JORDAN PO BOX 1500 HUNTSVILLE AL 34807-3801
3	COMMANDER US ARMY RESEARCH OFFICE K IYER J BAILEY S F DAVIS PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709-2211
1	NAVAL AIR WARFARE CTR S A FINNEGAN BOX 1018 RIDGECREST CA 93556
4	COMMANDER NAVAL WEAPONS CENTER N FASIG CODE 3261 T T YEE CODE 3263 D THOMPSON CODE 3268 W J MCCARTER CODE 6214 CHINA LAKE CA 93555
12	COMMANDER NAVAL SURFACE WARFARE CTR DAHLGREN DIVISION H CHEN D L DICKINSON CODE G24 C R ELLINGTON C R GARRETT CODE G22 W HOLT CODE G22 W E HOYE G22 R MCKEOWN JOHN M NELSON M J SILL CODE H11 WILLIAM J STROTHER A B WARDLAW JR L F WILLIAMS CODE G33 17320 DAHLGREN RD DAHLGREN VA 22448

NO. OF COPIES	ORGANIZATION
5	AIR FORCE ARMAMENT LAB AFATL DLJW W COOK M NIXON AFATL DLJR J FOSTER AFATL MNW LT D LOREY R D GUBA EGLIN AFB FL 32542
1	USAF PHILLIPS LABORATORY VTSI ROBERT ROYBAL KIRTLAND AFB NM 87117-7345
2	USAF PHILLIPS LABORATORY PL WSCD F ALLAHDADI PV VTA D SPENCER 3550 ABERDEEN AVE SE KIRTLAND AFB NM 87117-5776
5	WRIGHT LABS MNMW J W HOUSE ARMAMENT DIRECTORATE STE 326 B1 R D HUNT B MILLIGAN B C PATTERSON W H VAUGHT 101 W EGLIN BLVD EGLIN AFB FL 32542-6810
1	AFIT ENC D A FULK WRIGHT PATTERSON AFB OH 45433
6	LOS ALAMOS NATIONAL LABORATORY L HULL MS A133 J V REPA MS A133 C WINGATE MS D413 E J CHAPYAK MS F664 P HOWE MS P915 J KENNEDY MS P915 PO BOX 1663 LOS ALAMOS NM 87545

NO. OF COPIES	ORGANIZATION
39	SANDIA NATIONAL LABORATORIES ATTN MAIL SERVICES MS-0100 E W REECE MS 0307 D P KELLY MS 0307 L WEIRICK MS 0327 R TACHAU MS 0425 D LONGCOPE MS 0439 D HAYES MS 0457 J ASAY MS 0458 W TEDESCHI MS 0482 J SCHULZE MS 0483 P A LONGMIRE MS 0560 J COREY MS 0576 E S HERTEL JR MS 0819 A ROBINSON MS 0819 T TRUCANO MS 0819 J M MCGLAUN MS 0819 M VIGIL MS 0819 R BRANNON MS 0820 J ANG MS 0821 M BOSLOUGH MS 0821 L CHHABILDAS MS 0821 D CRAWFORD MS 0821 M FURNISH MS 0821 C HALL MS 0821 W REINHART MS 0821 P STANTON MS 0821 M KIPP DIV 1533 P YARRINGTON DIV 1533 J MCGLAWA DIV 1541 M FORRESTAL DIV 1551 R LAFARGE DIV 1551 C HILLS DIV 1822 R O NELLUMS DIV 9122 P TAYLOR ORG 1432 B LEVIN ORG 7816 L N KMETYK R REEDER J SOUTHWARD C KONRAD K LANG PO BOX 5800 ALBUQUERQUE NM 87185-0100

NO. OF COPIES	ORGANIZATION
3	DIRECTOR LLNL PHYSICS DEPT D A YOUNG T W BARBEE III F J ROGERS LIVERMORE CA 94551
4	DIRECTOR LLNL MS L35 R E TIPTON D BAUM M MURPHY T MCABEE PO BOX 808 LIVERMORE CA 94550
2	DIRECTOR LLNL MS L125 D R FAUX N W KLINO PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL R BARKER L159 PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL MS L180 G SIMONSON PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL F A HANDLER L182 PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL D WOOD L352 PO BOX 808 LIVERMORE CA 94550

NO. OF COPIES	ORGANIZATION
1	DIRECTOR LLNL S G COCHRAN L389 PO BOX 808 LIVERMORE CA 94550
3	DIRECTOR LLNL MS L495 D GAVEL J HUNTER E JOHANSSON PO BOX 808 LIVERMORE CA 94550
1	DIRECTOR LLNL R M KUKLO L874 PO BOX 808 LIVERMORE CA 94550
4	ENERGETIC MATERIALS RSCH TSTNG CTR NEW MEXICO TECH D J CHAVEZ M LEONE L LIBERSKY F SANDSTROM CAMPUS STATION SOCORRO NM 87801
3	NASA JOHNSON SPACE CENTER E CHRISTIANSEN J L CREWS F HORZ MAIL CODE SN3 2101 NASA RD 1 HOUSTON TX 77058
1	APPLIED RESEARCH LAB J A COOK 10000 BURNETT ROAD AUSTIN TX 78758

NO. OF COPIES	ORGANIZATION
4	SOUTHWEST RESEARCH INSTITUTE C ANDERSON S A MULLIN J RIEGEL J WALKER PO DRAWER 28510 SAN ANTONIO TX 78228-0510
2	AEROJET J CARLEONE S KEY PO BOX 13222 SACRAMENTO CA 95813-6000
2	AEROJET ORDNANCE P WOLF G PADGETT 1100 BULLOCH BLVD SOCORRO NM 87801
3	ALLIANT TECHSYSTEMS INC R STRYK G R JOHNSON MN11-1614 P SWENSONMN11-2720 600 SECOND ST NE HOPKINS MN 55343
1	M L ALME 2180 LOMA LINDA DR LOS ALAMOS NM 87544-2769
2	APPLIED RESEARCH ASSOC INC D GRADY F MAESTAS SUITE A220 4300 SAN MATEO BLVD NE ALBUQUERQUE NM 87110
1	APPLIED RESEARCH LABORATORIES T M KIEHNE PO BOX 8029 AUSTIN TX 78713-8029
1	ATA ASSOCIATES W ISBELL PO BOX 6570 SANTA BARBARA CA 93111

NO. OF COPIES	ORGANIZATION
1	BATTELLE R M DUGAS 7501 S MEMORIAL PKWY SUITE 101 HUNTSVILLE AL 35802-2258
3	BOEING AEROSPACE CO SHOCK PHYSICS & APPLIED MATH ENGINEERING TECHNOLOGY R HELZER T MURRAY J SHRADER PO BOX 3999 SEATTLE WA 98124
1	BOEING HOUSTON SPACE STN R F GRAVES BOX 58747 HOUSTON TX 77258
5	COMPUTATIONAL MECHANICS CONSULTANTS J A ZUKAS (5 CP) PO BOX 11314 BALTIMORE MD 21239-0314
1	DEFENSE TECHNOLOGY INTL INC D E AYER THE STARK HOUSE 22 CONCORD ST NASHUA NH 03060
3	DYNA EAST CORP P C CHOU R CICCARELLI W FLIS 3620 HORIZON DRIVE KING OF PRUSSIA PA 19406
1	R J EICHELBERGER 409 W CATHERINE ST BEL AIR MD 21014-3613
3	ENIG ASSOCIATES INC J ENIG D J PASTINE M COWPERTHWAITE SUITE 500 11120 NEW HAMPSHIRE AVE SILVER SPRING MD 20904-2633

NO. OF COPIES	ORGANIZATION
1	EXPLOSIVE TECHNOLOGY M L KNAEBEL PO BOX KK FAIRFIELD CA 94533
1	GB TECH LOCKHEED J LAUGHMAN 2200 SPACE PARK SUITE 400 HOUSTON TX 77258
2	GB TECH LOCKHEED L BORREGO C23C J FALCON JR C23C 2400 NASA ROAD 1 HOUSTON TX 77058
6	GDLS 38500 MOUND RD W BURKE MZ436 21 24 G CAMPBELL MZ436 30 44 D DEBUSSCHER MZ436 20 29 J ERIDON MZ436 21 24 W HERMAN MZ 435 01 24 S PENTESCU MZ436 21 24 STERLING HTS MI 48310-3200
1	GRC INTERNATIONAL T M CUNNINGHAM 5383 HOLLISTER AVE SANTA BARBARA CA 93111
1	RAYTHEON MSL SYS CO T STURGEON BLDG 805 M/S D4 PO BOX 11337 TUCSON AZ 85734-1337
5	INST OF ADVANCED TECHNOLOGY UNIVERSITY OF TX AUSTIN S J BLESS J CAZAMIAS J DAVIS H D FAIR D LITTLEFIELD 4030-2 W BRAKER LN AUSTIN TX 78759

NO. OF COPIES	ORGANIZATION
1	INTERNATIONAL RESEARCH ASSOC D L ORPHAL 4450 BLACK AVE PLEASANTON CA 94566
1	ITT SCIENCES AND SYSTEMS J WILBECK 600 BLVD SOUTH SUITE 208 HUNTSVILLE AL 35802
1	R JAMESON 624 ROWE DR ABERDEEN MD 21001
1	KAMAN SCIENCES CORP D L JONES 2560 HUNTINGTON AVE SUITE 200 ALEXANDRIA VA 22303
1	D R KENNEDY & ASSOC INC D KENNEDY PO BOX 4003 MOUNTAIN VIEW CA 94040
1	LOCKHEED MARTIN ELEC & MSLS G W BROOKS 5600 SAND LAKE RD MP 544 ORLANDO FL 32819-8907
1	LOCKHEED MARTIN MISSLE & SPACE W R EBERLE PO BOX 070017 HUNTSVILLE AL 35807
3	LOCKHEED MARTIN MISSILE & SPACE M A LEVIN ORG 81 06 BLDG 598 M R MCHENRY T A NGO ORG 81 10 BLDG 157 111 LOCKHEED WAY SUNNYVALE CA 94088
4	LOCKHEED MISSILE & SPACE CO J R ANDERSON W C KNUDSON S KUSUMI 0 81 11 BLDG 157 J PHILLIPS 0 54 50 PO BOX 3504 SUNNYVALE CA 94088

NO. OF COPIES	ORGANIZATION
1	LOCKHEED MISSILE & SPACE CO R HOFFMAN SANTA CRUZ FACILITY EMPIRE GRADE RD SANTA CRUZ CA 95060
1	MCDONNELL DOUGLAS ASTRONAUTICS CO B L COOPER 5301 BOLSA AVE HUNTINGTON BEACH CA 92647
1	NETWORK COMPUTING SERVICES INC T HOLMQUIST 1200 WASHINGTON AVE S MINNEAPOLIS MN 55415
4	ORLANDO TECHNOLOGY INC D A MATUSKA M GUNGER J OSBORN R SZEZEPANSKI 4565 COMMERCIAL DR #A NICEVILLE FL 32578
1	PHYSICAL SCIENCES INC P NEBOLSINE 20 NEW ENGLAND BUS CTR ANDOVER MA 01810
5	PRIMEX TECHNOLOGIES INC G FRAZIER L GARNETT D OLIVER D TUERPE J COFFENBERRY 2700 MERCED ST SAN LEANDRO CA 94577-0599
1	RAYTHEON ELECTRONIC SYSTEMS R LLOYD 50 APPLE HILL DRIVE TEWKSBURY MA 01876
1	ROCKWELL INTERNATIONAL ROCKETDYNE DIVISION H LEIFER 16557 PARK LN CIRCLE LOS ANGELES CA 90049

NO. OF COPIES	ORGANIZATION
1	ROCKWELL MISSILE SYS DIV T NEUHART 1800 SATELLITE BLVD DULUTH GA 30136
1	SAIC M W MCKAY 10260 CAMPUS POINT DR SAN DIEGO CA 92121
2	SOUTHERN RESEARCH INSTITUTE L A DECKARD D P SEGERS PO BOX 55305 BIRMINGHAM AL 35255-5305
5	SRI INTERNATIONAL J D COLTON D CURRAN R KLOOP R L SEAMAN D A SHOCKEY 333 RAVENSWOOD AVE MENLO PARK CA 94025
1	TRACOR ARSPC MINE CNTRMN DIV R E BROWN BOLLINGER CANYON SAN RAMON CA 94583
1	ZERNOW TECHNICAL SVCS INC L ZERNOW 425 W BONITA AVE SUITE 208 SAN DIMAS CA 91773
	ABERDEEN PROVING GROUND
51	DIR USARL AMSRL WM, I MAY AMSRL WM BC A ZIELINSKI AMSRL WM BE S L HOWARD AMSRL WM BD R PESCE-RODRIGUEZ A J KOTLAR AMSRL WM MB G GAZONAS

NO. OF
COPIES ORGANIZATION

ABERDEEN PROVING GROUND (CONTINUED)

AMSRL WM MC
J M WELLS
AMSRL WM T
B BURNS
T W WRIGHT
AMSRL WM TA
M BURKINS
W GILLICH
W BRUCHEY
G FILBEY
W A GOOCH
H W MEYER
E J RAPACKI
J RUNYEON
AMSRL WM TB
R FREY
P BAKER
R LOTTERO
J STARKENBERG
AMSRL WM TC
T W BJERKE
R COATES
K KIMSEY
M LAMPSON
D SCHEFFLER (10 CP)
S SCHRAML
G SILSBY
B SORENSEN
R SUMMERS
W WALTERS
AMSRL WM TD
A M DIETRICH
D DANDEKAR
K FRANK
M RAFTENBERG
A RAJENDRAN
G RANDERS-PEHRSON LLNL
M SCHEIDLER
S SCHOENFELD
S SEGLETES
T WEERISOORIYA
AMSRL WM TE
J POWELL
A PRAKASH

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
April 2000

3. REPORT TYPE AND DATES COVERED
Final, Nov 98 - Aug 99

4. TITLE AND SUBTITLE
Impact Effects in Multilayered Plates

5. FUNDING NUMBERS
1L162618AH8.0

6. AUTHOR(S)
Jonas A. Zukas* and Daniel R. Scheffler

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRL-WM-TC
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-2223

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
* Computational Mechanics Consultants, Inc.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report presents results of numerical simulations of impact effects in monoblock and mulitlayered plates using both Lagrangian and Eulerian wave propagation codes. It is found that Lagrangian simulations compare favorably with experimental and analytical results. Eulerian codes, while ideal for large distortion situations such as penetration, have great difficulty in describing multiplate perforation due primarily to problems with the interface treatment in Eulerian codes.

This report was originally presented as a paper at the Special Symposium Honoring the 70th Birthdays of Professors Jack Vinson and Charlie Bert, which was part of the 1999 ASME International Mechanical Engineering Congress and Exposition held in Nashville, TN, on 14–19 November 1999. The paper has been accepted for publication in a special volume of *The Journal on Solid and Structures.*

14. SUBJECT TERMS
numerical simulation, Eulerian methods, Lagrangian methods, finite elements, finite differences, high velocity impact, shock waves, multilayered plates

15. NUMBER OF PAGES
26

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-2223 (Zukas) ________ Date of Report April 2000

2. Date Report Received ________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ________

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ________

CURRENT ADDRESS

Organization

Name E-mail Name

Street or P.O. Box No.

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

Organization

Name

Street or P.O. Box No.

City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)